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# The Berkeley Accelerator Space Effects (BASE) Facility

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**ABSTRACT** – *The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory - a Department of Energy (DOE) multipurpose laboratory - is now being jointly funded by the DOE, the U.S. Air Force (USAF) and the National Reconnaissance Office (NRO). The Cyclotron is now running about 50% of the time using the BASE facility for radiation effects testing with heavy ions and protons. A neutron test facility is under construction.*

## I. INTRODUCTION

The 88-Inch Cyclotron at Lawrence Berkeley Laboratory, operated by the University of California for the US Department of Energy (DOE), is a K=140 sector-focused cyclotron with both light- and heavy-ion capabilities. Protons and other light-ions are available at high intensities (10-20 pμA) up to maximum energies of 55 MeV (protons), 65 MeV (deuterons), 135 MeV ($^{3}$He) and 140 MeV ($^{4}$He). Most heavy ions through uranium can be accelerated to maximum energies which vary with the mass and charge state.

In 2003, the DOE announced plans to close the 88-Inch Cyclotron as a DOE National User Facility in FY04. This was a major blow to heavy ion testing in the United States, as neither of the other facilities at Brookhaven National Lab or Texas A&M University could provide the beams and/or the hours that the 88-Inch provided to the community. Recognizing this, Aerospace Corporation identified funding within the US Air Force Space Missile Command (USAF-SMC) and National Reconnaissance Office (NRO) to provide 40% of the operating funds of the Cyclotron in FY04 and FY05. A Memo of Understanding (MOU) was signed by DOE and the two Defense agencies, wherein DOE agreed to continue funding the Cyclotron at the 60% level. Included in the MOU was a plan to explore funding beyond FY05, and pursuant to this a Memo of Agreement was signed by all parties in April 2005 which extends funding for five years, through FY2011.

Thus the 88-Inch Cyclotron was reborn with a dual mission: 1) an in-house basic research program in nuclear science to serve LBNL and UC Berkeley scientists and students, and 2) a state-of-the-art, multifaceted radiation effects facility – the Berkeley Accelerator Space Effects (BASE) Facility - to serve the National Space Security community funded by USAF-SMC and NRO. When time is available, the BASE facility is also used by commercial and other government agencies on a cost recovery basis and for LBNL experiments in radiation biology. In addition, a neutron beam line has been funded under a third program: a DOE-NNSA Academic Alliance grant to measure neutron cross sections on unstable targets for stockpile stewardship and nuclear astrophysics. Quasi-monoenergetic and white spectrum neutrons in the range of 10-32 MeV will be available for radiation testing as well once the dosimetry is complete.

## II. RADIATION TESTING AT THE 88-INCH CYCLOTRON

In a cyclotron, the cyclotron frequency $f$ is given by

$$f = qB/(2\pi m) \qquad [1]$$

where q and m are the charge and mass of the ion, respectively, and B is the magnetic field. Thus the mass resolution of the cyclotron is directly proportional to the frequency resolution. For the 88-Inch, the frequency resolution is 2 kHz, which translates to a mass resolution of ≈1/3000. At this level, the cyclotron can separate most – but not all – ions of near-identical mass-to-charge (m/q) ratio emanating from the ion source. [1] This fundamental limitation of cyclotrons was turned to an advantage for detector calibrations and device testing with the understanding that several different beams could be delivered to an experiment with a minimum of retuning. By the late 1970s, single event effect (SEE) testing was occurring on a small scale. Some effects discovered at LBNL by Aerospace Corporation include the first single event latchup (SEL) (1979), the variation of SEL sensitivity with device temperature (1986) and single event transients (SET) in digital devices (1987). [2]

Radiation effects testing with heavy ions using the 88-Inch came into its own when the first electron cyclotron resonance (ECR) ion source was coupled to the Cyclotron in the early 1980s, the first such combination in the world. [3] With the ECR source, it was very easy to ionize a mixture of noble gases to an integer m/q (2, 3, 4, 5) to make a “cocktail” of beams of near-identical m/q. [4] This proved very beneficial in SEE testing since users could switch from ion to ion with a minimum of tuning time. Cyclotron staff developed a “light-ion cocktail” of fully-stripped m/q=2 ions (through $^{36}$Ar) and a “heavy-ion cocktail” of m/q = 5 at 4.5 AMeV. This latter cocktail was available through xenon from the LBNL ECR.

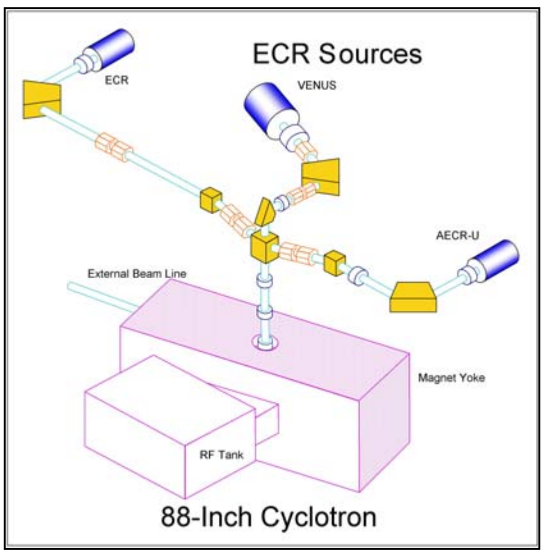


Figure 1. The 88-Inch Cyclotron and its present (ECR and AECR-U) and future (Venus) electron cyclotron resonance ion sources.

In the early 1990s, the ion source group built a second state-of-the-art ECR source, the Advanced ECR (AECR) source. [5] A schematic layout of the Cyclotron with its present and future ECR sources is shown in Figure 1. With the AECR, it was possible to obtain $Bi^{+41}$, which at m/q = 5.1, could be accelerated together with the 4.5 AMeV cocktail. At a linear energy transfer (LET) value of 98 MeV/mg/cm$^2$, this was very useful for testing radiation-resistant electronics. Throughout the decade of the 1990s, improvements were made in the ion sources and cyclotron vacuum which were of benefit to both the nuclear science and radiation effect users alike. A new cocktail was developed at 10 AMeV, which allowed ions as heavy as xenon to penetrate silicon to depths of greater than 100 μm; this was important because chips were becoming increasingly more complex and difficult to delid. More recently, a 16 AMeV cocktail has been developed with ions as heavy as krypton.

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In addition to the heavy ion capability, the 88-Inch Cyclotron was originally designed as a light ion accelerator and thus has massive shielding (the vault shielding was designed for milliamps of deuterons). This allows the safe operation with reasonably high intensities of protons, useful for total dose testing. It will also enable the production of reasonably high fluxes of neutrons. Proton testing has become an increasingly important component of BASE operation, as can be seen in Figure 2. In FY04, the new BASE facility used approximately 40% of the total scheduled time, about 1500 hours/year..

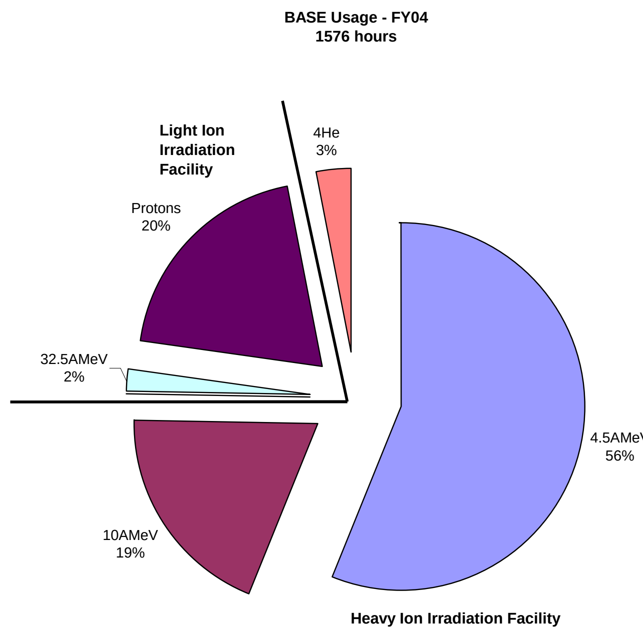


Figure 2. Beams used by the BASE facility in FY04.

## III. THE BASE FACILITY

The layout of the 88-Inch Cyclotron facility and the beamlines which are part of BASE is shown in Figure 3. Heavy ion testing takes place in the vacuum chamber in Cave 4B. The light ion testing has recently been moved to the neighboring Cave 4A, with a trailer on the roof above the two caves acting as a counting area for both facilities. Cave 2 has been modified for Phase 1 neutron irradiations and is presently being commissioned.

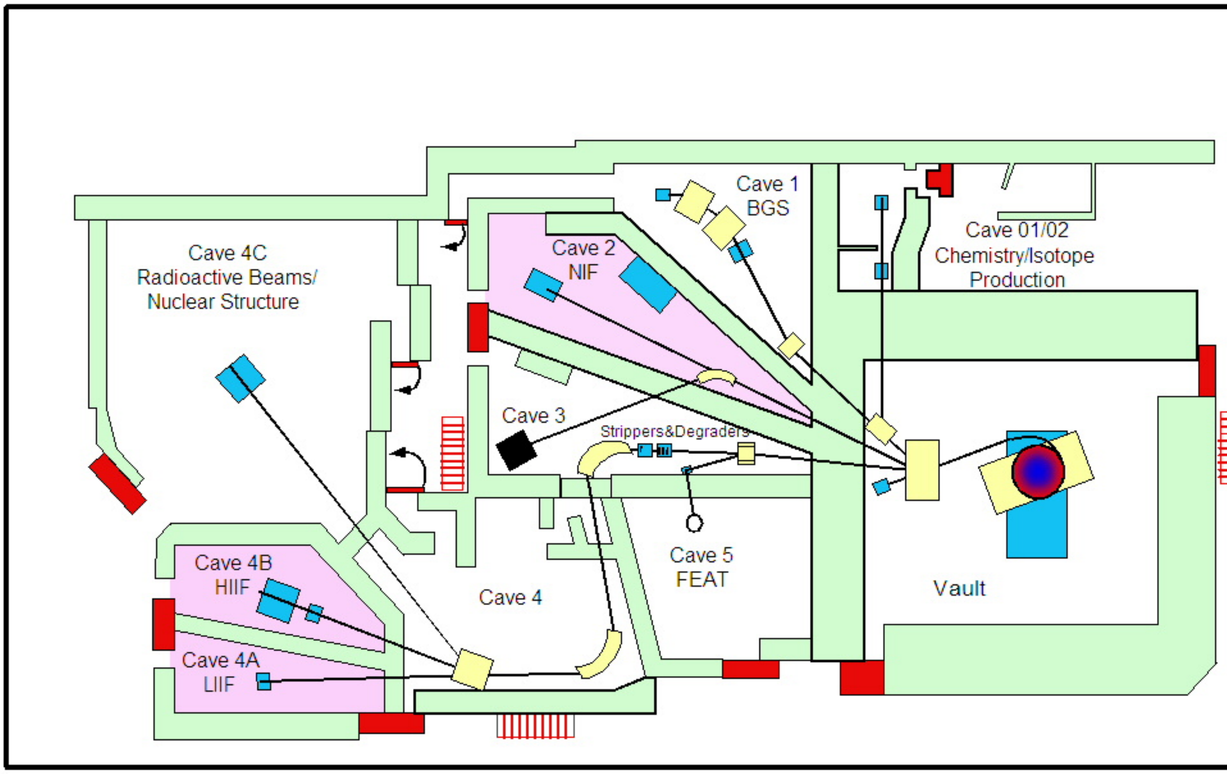


Figure 3. Map of 88-Inch Cyclotron Facility. The shaded areas are the beamlines which are present or future parts of the BASE facility.

*III.A. The Heavy Ion Irradiation Facility (Cave 4B)*

Heavy ion testing takes place in the vacuum chamber located in Cave 4B. Three heavy ion cocktails have been developed at energies of 4.5, 10 and 16 AMeV and are summarized in the first three rows of Table 1. For each listed cocktail, a group of standard ions are listed which are regularly available. The 16 AMeV cocktail is a recent addition and is available through krypton, at a linear energy transfer (LET) (at the surface) of 26 MeV/mg/cm2 and a range of almost 700 μm. [6] It is possible to run this cocktail in air if needed although the energy at the device-under-test (DUT) will be degraded to ≈9 AMeV. Work is in progress to develop dosimetry for the new Light Ion Irradiation Facility (see next section) which will enable use of the 16 AMeV cocktail in Cave 4A, where the cable lengths are only 10 feet, and test equipment can be located very close to the device.

Of course, the appropriate LET to use in calculations of Weibull curves for heavy ion single event effects is that for the sensitive depth of the device, with all interceding layers taken into account. For the heavier ions, this will be much different than the surface LET. Figures 4-6 give the LET versus depth in silicon for the three heavy ion cocktails of Table 1. These curves were calculated assuming no other layer than silicon using SRIM 2003. [7]

Three major improvements to the BASE facility have been implemented in the past year, with others in the progress, in order to meet our goals of improved customer service, reliability and quality assurance. Along with these improvements, much of the support and maintenance of the heavy ion facility has been transferred from Aerospace Corporation to 88” Operations staff.

The first improvement is the addition of a dedicated support person to take care of the facility. With the usage expected to continue to increase in the future, this becomes very important.

Secondly, the control system and user interface has been converted to a PC-based LABVIEW™ system from the original Macintosh system written at Aerospace Corporation. This enables the 88-Inch staff to maintain and upgrade both the hardware and software. The new system was implemented in September 2004 and has been well received by the users.

The third improvement has been to upgrade the dosimetry system. The system in use until recently was designed when SEU measurements at low doses was the standard operating mode. The plastic scintillator material which is commonly used for dosimetry degrades under high doses, particulary when using high LET ions such as xenon and bismuth. We have seen in some cases visible ‘browning’ of the material in a few hours when using $10^5$ ions/sec of bismuth. Therefore, we have replaced the plastic scintillator in the outer ring of the dosimetry system with an inorganic scintillator, YAP(Ce). The YAP(Ce) has the disadvantage of being slower and more expensive than plastic, but the increased life time is substantial. The new system has been running for several months now and shows no sign of degradation. Now the high flux limit is due to saturation of the photomultiplier tubes. We are investigating lower gain tubes which may alleviate this problem; meanwhile, high flux runs are accommodated by collimation.

Table 1. Summary of standard BASE cocktails and other beams. Other ions and energies are available by special arrangement.

| Cocktail (AMeV) | Standard Ions (st) | Other Ions[a] | LET (MeV/mg/cm$^{2}$)* | Range in Si (μm)* |
|---|---|---|---|---|
| 4.5 | $^{15}$N, $^{20}$Ne, $^{40}$Ar, $^{59}$Co, $^{63}$Cu, $^{86}$Kr, $^{136}$Xe | HeH[b], $^{10}$B, $^{78}$Kr, $^{209}$Bi | 3.1-68.8 (st)<br>0.064-99.6 (all) | 43-67 (st)<br>41-180 (all) |
| 10 | $^{18}$O, $^{22}$Ne, $^{40}$Ar, $^{65}$Cu, $^{86}$Kr, $^{136}$Xe | $^{10}$B, $^{27}$Al, $^{51}$V, $^{73}$Ge, $^{98}$Mo | 2.2-59.1 (st)<br>0.89-59.1 (all) | 97-227 (st)<br>98-307 (all) |
| 16 | $^{12}$C, $^{14}$N, $^{17}$O, $^{20}$Ne, $^{40}$Ar, $^{63}$Cu, $^{78}$Kr | $^{28}$Si, $^{35}$Cl, $^{55}$Mn, | 0.93-25.7 (all) | 171-467 (all) |
| 32.5 | $^{4}$He, $^{12}$C, $^{14}$N, $^{16}$O, $^{20}$Ne, $^{36}$Ar$^{18+}$ | $^{2}$H, $H_2$[b], $^{28}$Si, $^{32}$S, $^{40}$Ca | 0.022-8.01 | 0.29-4.29 mm |
| Light Ion Tunes | $^{1}$H, $^{4}$He | | 0.009-0.342 | 93.4-14,430 |

* LETs and ranges in silicon calculated using SRIM 2003 [7].
[a] These ions require special arrangements and advance notice.
[b] LETs and Ranges for molecular ions are calculated for separate components after break-up in target or scattering foil.

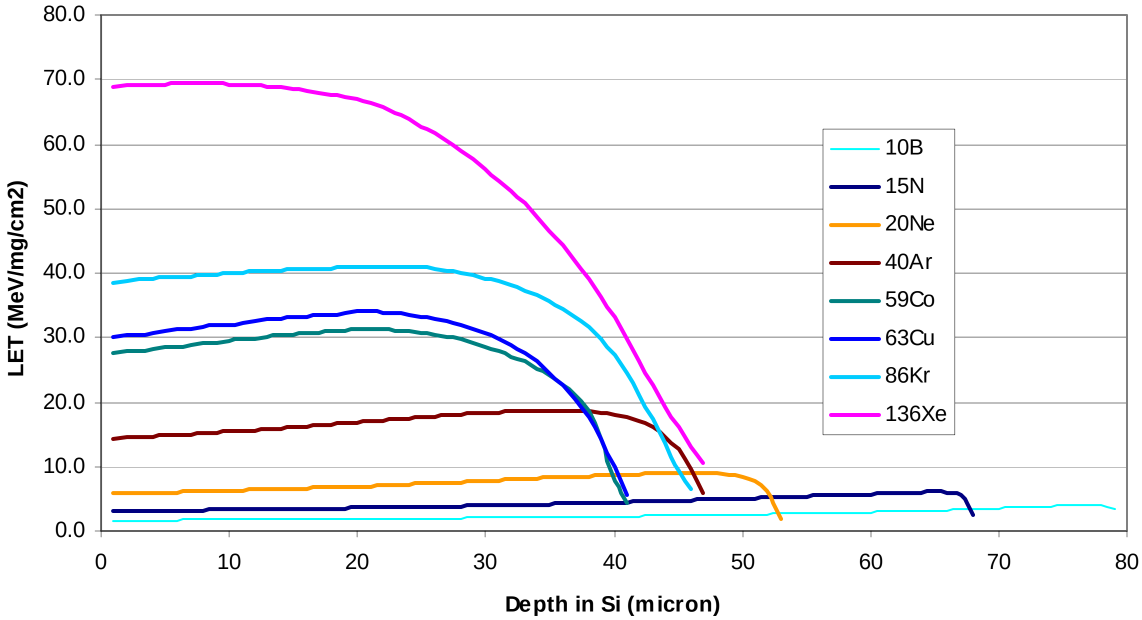


Figure 4. Linear Energy Transfer (LET) versus depth in silicon for the 4.5 AMeV cocktail.

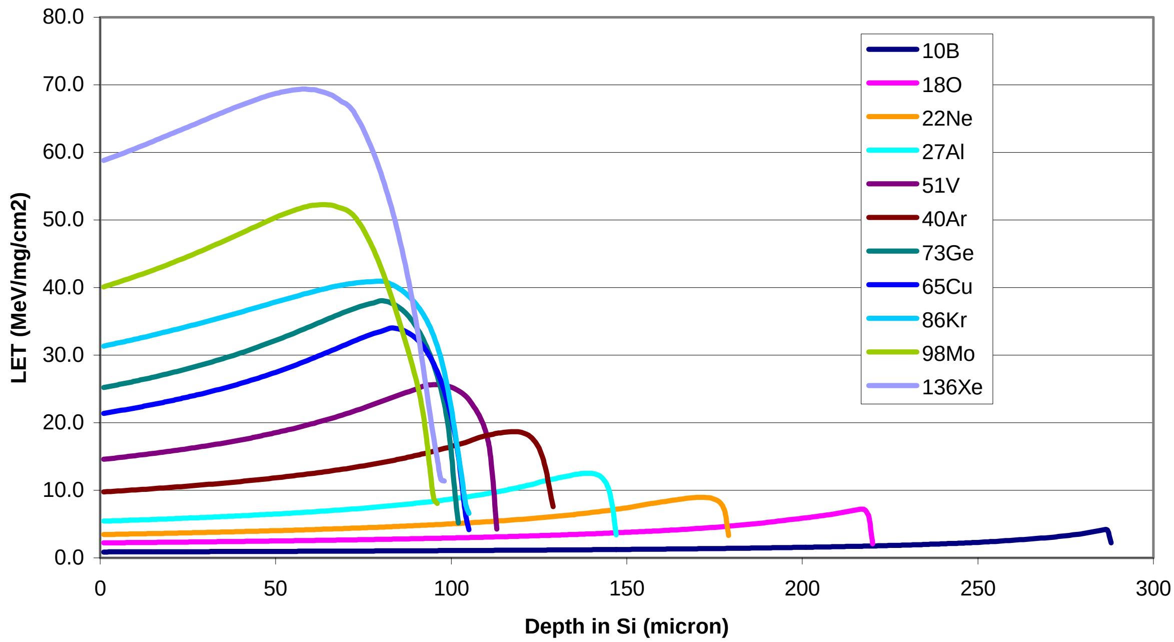


Figure 5. Linear Energy Transfer (LET) versus depth in silicon for the 10 AMeV cocktail.

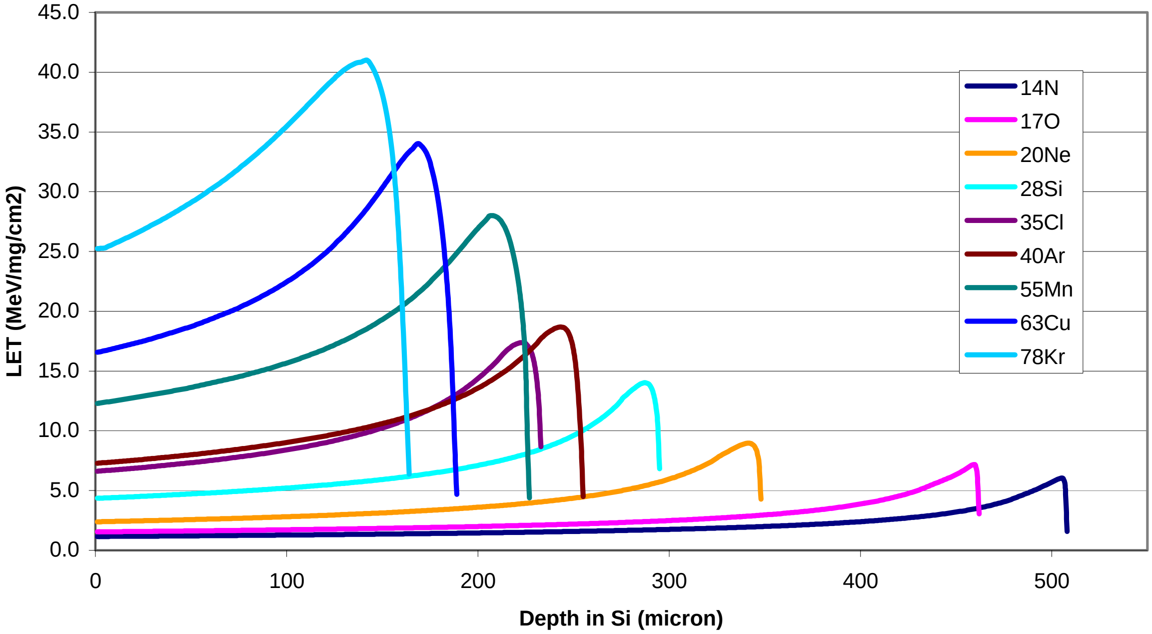


Figure 6. Linear Energy Transfer (LET) versus depth in silicon for the 16 AMeV cocktail.

### *III.B The Light Irradiation Facility (Cave 4B)*

The Light Ion Irradiation Facility (LIIF) is now operating in Cave 4A, which results in many improvements over the previous station in Cave 3b. These improvements include:

- Easier access
- Use of BASE counting shack for both beamlines
- A 10 ft cable run (compared with 30 ft )
- 6” beam window (compared to 4”)
- An ability to degrade the beam before the high resolution magnet system for easier energy changes

We are developing calibration procedures for the ion chamber used for dosimetry of protons.

## IV. FUTURE IMPROVEMENTS AND UPGRADES

### *IV.A. The Heavy Ion Irradiation Facility (Cave 4B)*

Within the next year, a third generation ion source, VENUS, will be coupled to the Cyclotron. This superconducting ECR source is operational and being commissioned. Preliminary measurements (not at full power) show an improvement of a factor of four in intensity for $Bi^{+41}$ [8]. This source will improve the intensity of all the heavier ions in the cocktail and allow us to extend some of the cocktails to higher LETs.

The next step in quality assurance for the heavy ion beams will be to make energy and contamination measurements a part of the standard operating procedure. At the present time, because the system is not very user friendly, this is only done when there is a question about the ion identification or contamination. While 88” Operations staff is quite confident in the purity of our cocktail beams, this has always been a question about the cocktail method.

In the next year, we expect to incorporate a memory chip which has a well characterized SEU cross section curve into the chamber as a quality assurance device. This chip will be on a lever arm so it can be dropped in front of the DUT and give a check on whether the upset cross section is within certain preset limits; this will ensure that all aspects of the beam delivery and dosimetry are working correctly.

### *IV.B. A Neutron Irradiation Facility (Cave 2)*

A neutron capability is being developed at the Cyclotron which will be available for radiation effects testing. In Phase 1, to be finished in 2005, a white spectrum of neutrons will be available for RET. Neutron dosimetry is being developed for this application. In Phase 2, quasi-monoenergetic beams will be available in the range of 10-32 MeV, as well as a beam around 200 keV. These energies of beams are useful for ground based soft error rate studies and for studies related to lunar and Martian surface enclosures, e.g. shielding studies, radiation biology and radiation effects on materials and electronics.

## V. CONCLUSIONS

The BASE Facility has become an important part of the test community for both heavy ion and proton testing. and has funding assured for five more years. The heavy ion facility in Cave 4B continues to be improved to meet the needs of the community and assure quality control and reliability. New beams have been developed and once the VENUS ion source has been coupled to the Cyclotron (scheduled for FY06) higher intensities of the high-LET ions will be available. The light ion facility has been relocated and improved. With the addition of neutron testing (scheduled for later this year), the BASE facility at the LBNL 88-Inch Cyclotron will serve the radiation effects testing community with a versatility not found

## VI. ACKNOWLEDGMENTS

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